A Brief History and Research of the Supernova Remnant Cassiopeia A

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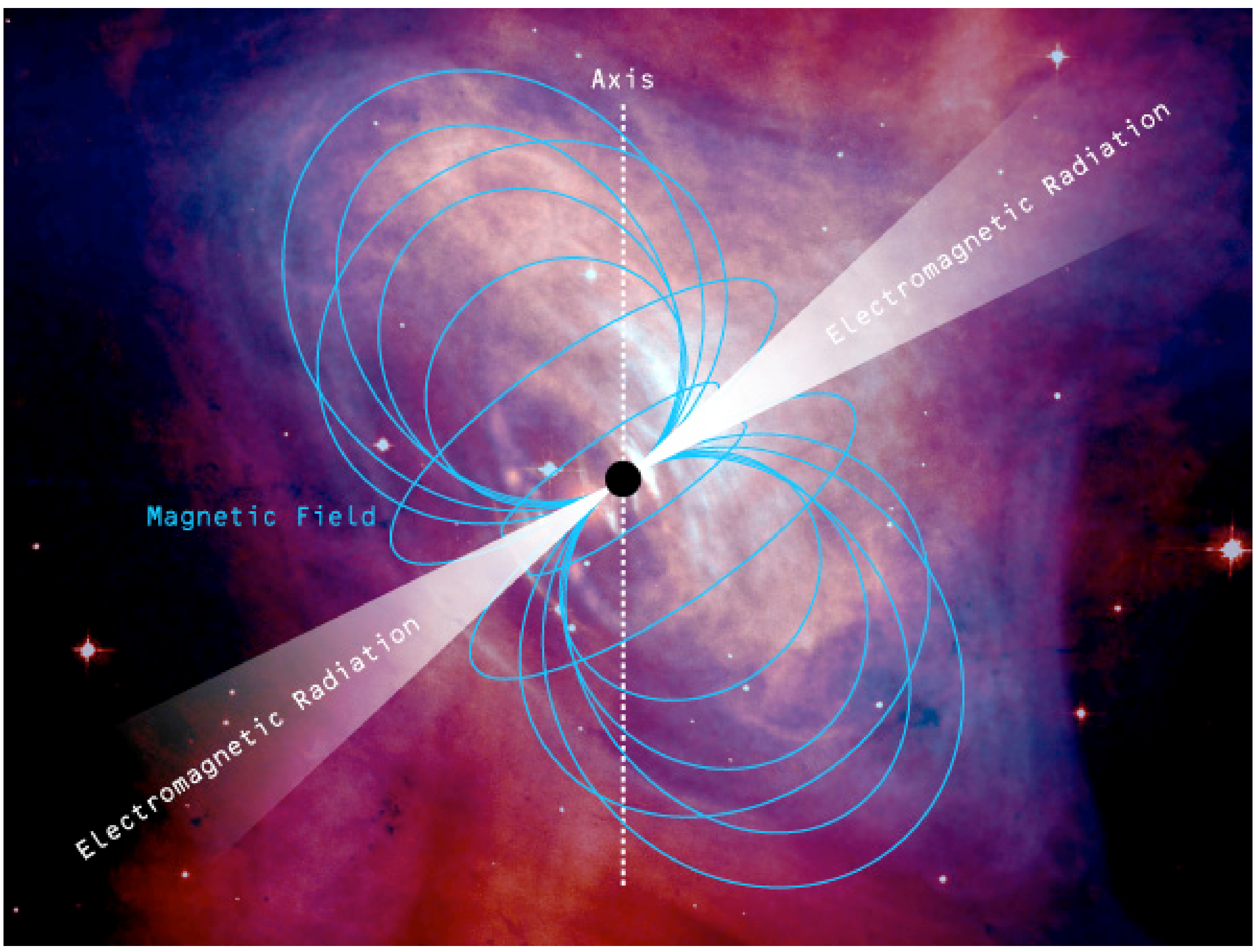
Over the last two decades scientists, have been fascinated by the compact object Cas A. Compact objects are products of a star after a supernova explosion. The term compact object includes phenomena related to the death of a star, such as neutron stars and black holes. When scientists are unsure of the identity of a supernova remnant, the object is classified as a compact object. The data gathered on Cas A has been truly puzzling to scientists in their attempt to classify the nature of Cas A. It has been hypothesized that Cas A is a neutron star. However, Cas A does not fit the classical model of a neutron star; it is questioned whether this hypothesis is correct.

Neutron Stars are the result after the gravitational collapse of a massive star, usually around the order of eight times the mass of the sun. A star shines because it is using nuclear fusion to produce electromagnetic radiation. As the star is producing nuclear fusion, it is also creating a huge outward force. This outward force does not cause the star to continue to expand because it is in equilibrium with the force of gravity. Stars have a huge amount of mass so that also means that the force of gravity is huge. Stars are mainly composed of hydrogen and use fusion to create heavier elements. Throughout a star's life it is continually creating heavier elements. However when a star reaches the element iron, it has reached the end of its life. Due to the properties of iron, it will not fuse to create any heavier elements. The force pushing the star outwards, which was fusion, no longer is acting on the star. Thus the opposing force to the star, gravity, takes over. A star collapses due to the overwhelming force of gravity. During the last seconds of the collapse, the iron core changes into neutronium. This is a state of matter where all the electrons and protons of the iron atoms are fused together to form a star entirely composed of neutrons. As the massive star collapses, its outer layers fall inward and bounce back off of the neutronium core causing a supernova (Haughian 2002). Due to the Pauli Exclusion Principle, the collapse stops and does not continue to form a black hole. The Pauli Exclusion Principle states that for a basic atom, no two electrons can have the same four quantum numbers; therefore the electrons will have different spins. Neutron Stars are usually within the range of 1.35 to 2.1 solar masses and have a diameter of 10km to 20km (Miller n.d.).

There are several types of neutron stars that occur: radio pulsars, x-ray pulsars, and magnetars, which are a subcategory of radio pulsars (Anissimov 2010). A neutron star keeps most of its angular momentum after the collapse. Since it is only a fraction of the diameter of its progenitor star, it spins very rapidly at high velocities and emits electromagnetic waves at the poles of the star. This angular momentum is from the progenitor star, since most main sequence stars begin life spinning. A neutron star that exhibits this behavior is called a pulsar (Pulsar n.d.). Pulsars have a very high magnetic field. This is because the neutron star holds on to the magnetic field that the progenitor star had. The magnetic field is not nearly as strong because the star was many times larger than the neutron star. The magnetic field creates a strong electric field. This electric field creates charged particles to flow out of the magnetic poles. As the charged particles spin around the magnetic field lines, they produce electromagnetic radiation. The radiation produced by pulsars is also called synchrotron radiation. A synchrotron is described to be a circular particle accelerator that uses synchronized magnetic fields and electric fields on a particle beam (Synchrotron radiation n.d.). The energetic jets at the poles of the neutron star act as synchrotrons. The magnetic poles are not always in line with the axis of rotation of the star. This is why there can be a pulsating effect. If the magnetic poles are on the side of the neutron star as it spins, it will appear to have pulses of radiation. Although most neutron stars begin life as a pulsar, we cannot identify it as a pulsar unless its electromagnetic beams are in the same plane as Earth because it will not appear to



This illustration is of the components of a pulsar. All neutron stars have magnetic fields, which in combination with the created electric field produce electromagnetic radiation at the magnetic poles. As this illustration demonstrates, the axis of the star and the magnetic poles of the star usually do not line up. Thus as the neutron star spins, the electromagnetic radiation travels around the side of the star. This is how the star appears to be pulsating (Wieck 2010).

be pulsating from our point of view. Neutron stars usually start off as pulsars, but lose angular momentum over time and slowly stop spinning. Radio pulsars are the most common form of neutron star (National Radio Astronomy Observatory n.d.). Radio pulsars emit radio waves at the poles of the star and only a handful of stars have their poles facing Earth. A radio pulsar is the name of a typical pulsar described above (Dr. Jim Lochner 1997-2010).

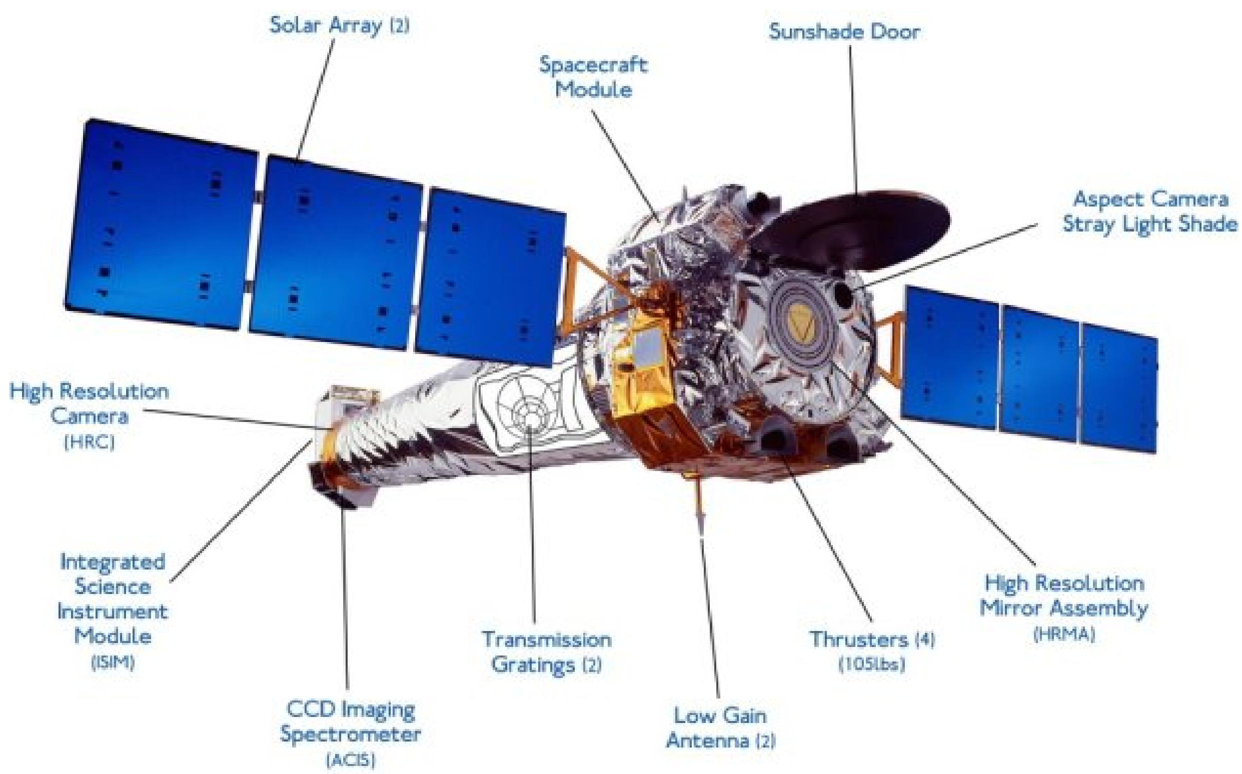
X-ray pulsars emit electromagnetic waves in the form of x-rays. These stars are powered by extremely hot inflowing matter instead of by their own rotation. X-ray pulsars usually fall under two categories: young, isolated neutron stars or millisecond pulsars. Millisecond pulsars emit x-rays every 0.01 seconds because they rotate at high velocities. These neutron stars spin at such high velocities because their companion star accelerates them. X-ray pulsars are commonly found as part of a binary system and steal matter from their companion star. However, if enough matter falls into the x-ray pulsar, it may collapse into a black hole. The electrical current in the magnetosphere of the pulsar is associated with the strongly pulsating x-rays, and the steady x-rays correlate with emissions from the surface of the neutron star. It is frequently found in pulsars that the x-ray pulses are in phase with the radio pulses. This implies that the electrical current producing the radio waves is also creating the x-rays. This however does not hold true for all pulsars, and in x-ray pulsars, the pulsed x-rays must come from a different area of the pulsar's magnetosphere than the radio waves (The Astrophysics Spectator 2007). Since x-ray pulsars are commonly found with neutron stars that are spinning rapidly, it can also be said that x-rays are common to young neutron stars. Neutron stars start off spinning at high velocities and slow down as they grow older (Dr. Jim Lochner 1997-2010).

Magnetars are the most exotic type of neutron star; they are produced from massive stars that spin rapidly. If the rotation is fast enough, the speed will match the inner convective currents of the massive star. This causes the magnetic field of the collapsing star to increase to extreme levels. The magnetic strength of a magnetar is in the order of ten gigateslas. An average neutron star has a magnetic field of 10^8 teslas and a main sequence star like our sun has a magnetic field of .0001 teslas (Duncan 1998). So magnetars have the most powerful magnetic fields in the universe (Magnetars n.d.).

Black holes are the final stage of life for an enormously massive star. The forming of a black hole starts the same as the forming of a neutron star. The only difference is that black holes come from more massive stars, usually stars in the order of ten times more massive than the sun. Like neutron stars, the core of the massive star forms neutronium, which the outer layers of the star bounce off of in a supernova. However, in the case of a black hole, the core of the star is still so massive that it continues to collapse and create a gravitational well commonly known as a black hole. The gravitational force is so strong in these circumstances that it overcomes the Pauli Exclusion Principle. There are three types of black holes; however only the stellar mass black hole is a candidate for a compact object, since the two other types are many times more massive than the sun (Black Holes n.d.).

After a supernova explosion of a star, a compact object is left. However, the object is not just the only trace left behind by the star. Compact objects tend to lie in the center of nebulae. Nebulae are the gas and matter of the star that was hurdled into space as a result of the explosion. Stars have several types of elements contained inside due to nuclear fusion. These gases are expelled during the supernova explosion and compose the nebula. Since each element has different properties, each refracts light differently. The result is several beautiful colors composing the nebula. This also means that are many types of electromagnetic waves radiating from the nebula. When scientists search for compact objects, they use telescopes that pick up certain wavelengths, commonly it is x-rays. The leading x-ray telescope in the field is called Chandra; it was launched July 23, 1999 (Harvard-Smithsonian Center for Astrophysics n.d.). It has helped make great progress in astronomy and astrophysics, and much of the information we have about compact objects was gathered through Chandra.

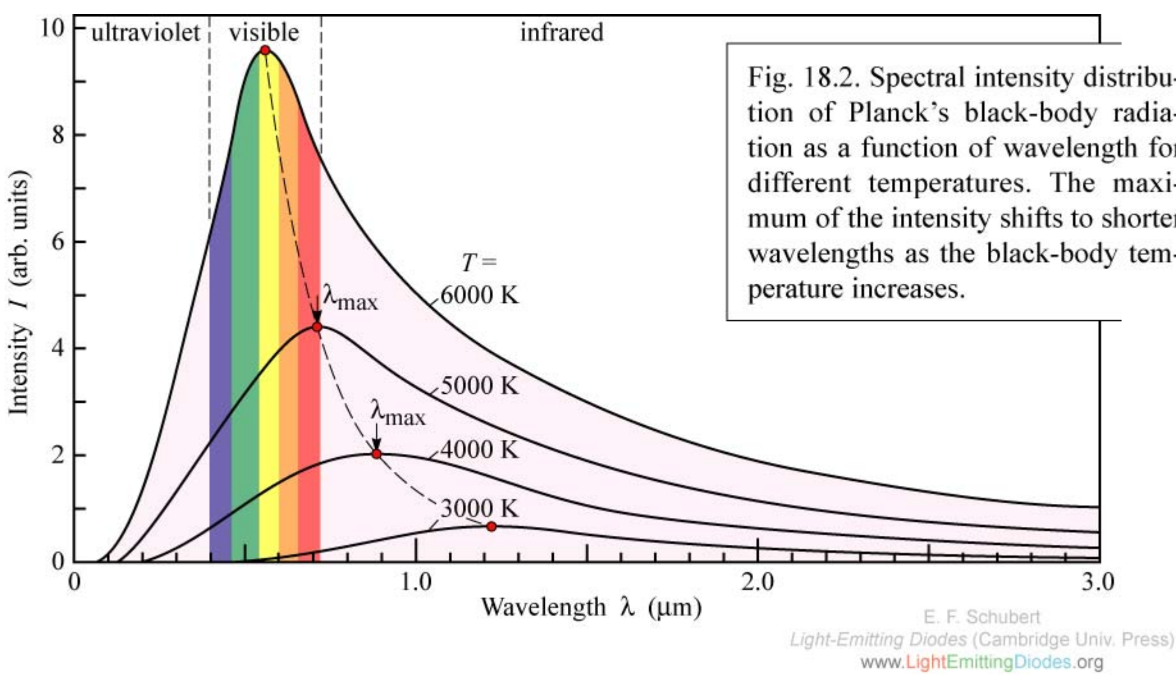
Astronomers and Astrophysicists focus satellite telescopes like Chandra on a certain region of space where a neutron star or other compact object is at, and collect data. In the case of Chandra, it has several methods of collecting data. It has a high resolution camera that takes images of x-rays given off by the object. Chandra also has ten charged coupled devices attached to the panels of the telescope. These devices are used in gathering spectral information on the object. In addition, Chandra has the High Energy Transmitting Grating Spectrometer, which captures x-rays emitted and measures them in electron volts (Harvard-Smithsonian Center for Astrophysics n.d.). Electron volts are the measurement of kinetic energy gained by one single unbound electron as it accelerates through an electric potential difference of one volt (Electron Volt n.d.). The reason electron volts are useful is because the energy of light is measured in electron volts. Scientists are concerned about the energy of light because it provides us with the light spectrum for a certain energy range. Through these instruments, several forms of data can be collected, which gives scientists a better picture of the object of study.



This illustration of the x-ray telescope Chandra shows all the parts used in collecting data (R.Nave 2000).

Through calculations and observations, scientists have developed models for neutron stars as well as for other compact objects. These models for neutron stars include blackbody radiation and x-ray spectral fitting with a power law model.

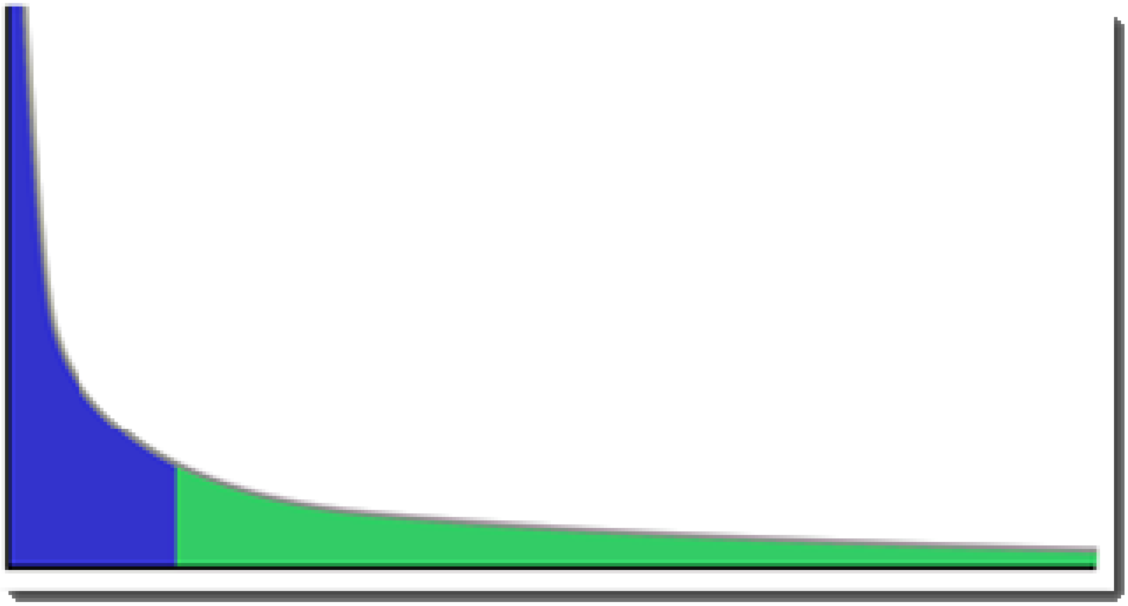
Blackbody radiation is electromagnetic radiation that is emitted from a blackbody, an object that absorbs all electromagnetic radiation, at a given temperature. Blackbodies absorb and luminously emit electromagnetic radiation in a distinct, continuous spectrum. A blackbody does however emit a temperature-dependent electromagnetic spectrum. This thermal radiation from a blackbody is referred to as blackbody radiation (G.Pattison 2000-2001).



This is an illustration of a blackbody curve that a star will radiate electromagnetic radiation. The graph is a representation of the relationship between Intensity and Wavelength. The steepest slope of the curve is the ultraviolet radiation, the maximum of the curve is visible light, and the gradual slope is the infrared radiation (Pol 2010).

The relation between wavelength, frequency, and temperature in a blackbody spectrum is as follows: the shorter the wavelength; the higher the frequency, and the higher frequency is also related to higher temperature. Consequently, a hotter object has a color that is closer to the blue end of the spectrum and a cooler object has a color that is closer to the red (G.Pattison 2000-2001). True blackbodies don't actually exist outside of theory. Stars are approximate blackbodies since they absorb as well as radiate most electromagnetic radiation. Neutron stars do emit blackbody radiation, but are not blackbody spheres like stars. Neutron stars emit electromagnetic radiation through the poles due to charged particles following the magnetic field lines out from the magnetic poles. This kind of blackbody generates a different model than a typical star would. Using this model of blackbody radiation, we can compare it to possible candidates for neutron stars and make a conclusion on the identity of the object.

X-ray spectral fitting is a process in which scientists make a model of a neutron star by using data such as the mass, the radius, and the composition of the atmosphere. Scientists make models of stars using computer code to mathematically represent the physical features. The computer can make assessments about the star based on the data that was used to create the model. Using a power law, which is defined as a mathematical relationship between two magnitudes (Power Law n.d.),

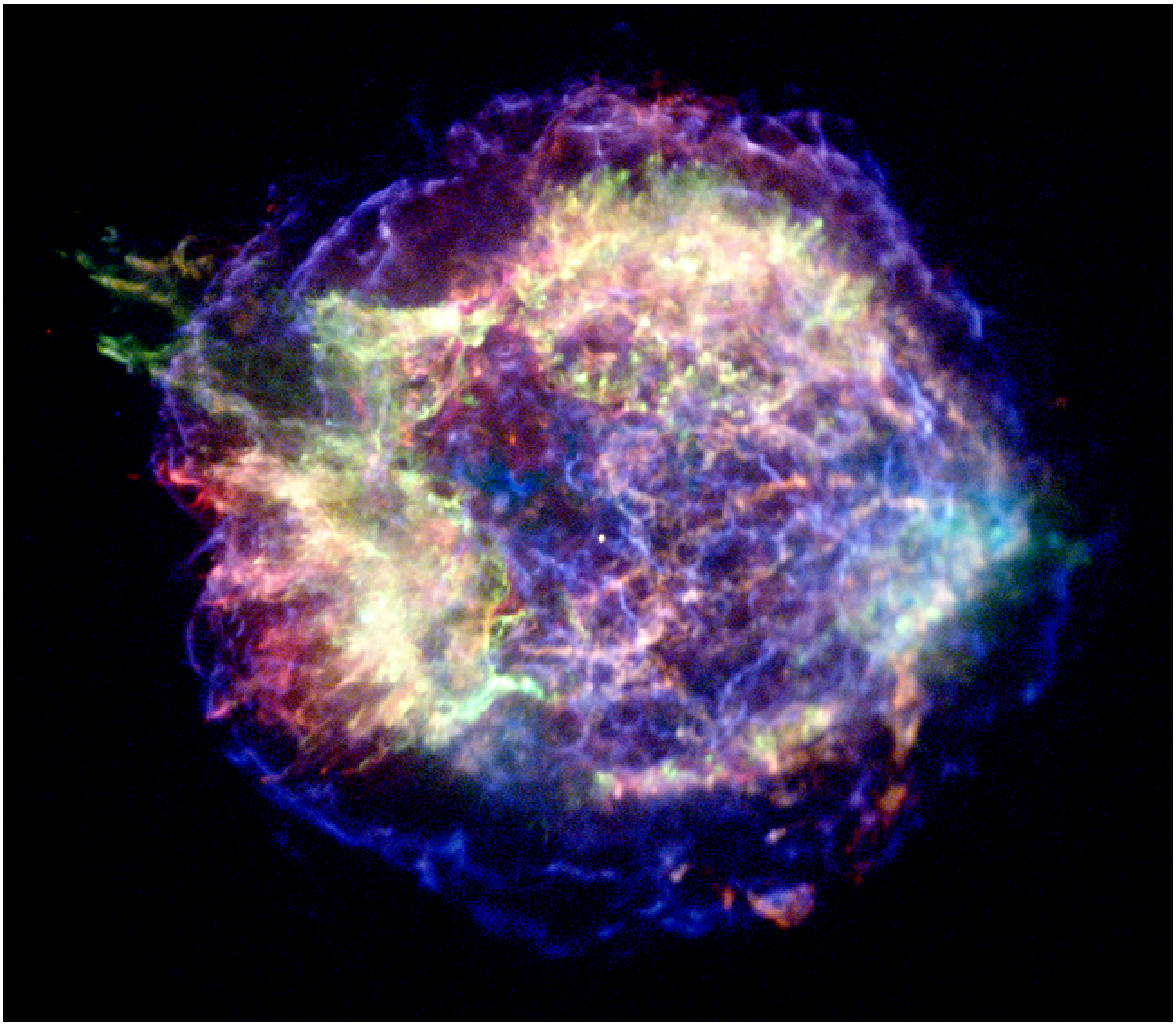


This illustration is of a graph representing the power law, a mathematical equation to express functions in relation to each other (Power Law n.d.).

scientists can observe the interactions between the blackbody radiation and synchrotron radiation. Using the data gathered from telescopes, we can compare it to the given models and try to determine the identification or certain properties of the neutron star. Comparing the wavelengths emitted by the neutron star, we can also determine the elements that are present.

An object of interest in terms of compact objects is the supernova remnant in the constellation Cassiopeia. Its given name is Cassiopeia A or Cas A for short.

(Cassiopeia A and Supernova 1680 or 1667 n.d.)



This is a photograph of the supernova remnant found in Cas A. This picture was taken using the Chandra telescope (Department of Physics and Astronomy 2009).

It is believed that Cas A is the product of a supernova that occurred in 1680 and observed by John Flamsteed, an English astronomer. It is debated on whether the supernova Flamsteed observed is the same as the supernova that produced Cas A. Calculations show that the supernova that produced Cas A should have occurred in 1667. Also the location that Flamsteed made his observation in the constellation

Cassiopeia is not where Cas A is located. Regardless of the exact specifics on the origin of Cas A, its age is established to be around 300 hundred years old (Deepto Chakrabarty 2001). Cas A is the youngest known supernova remnant in the Milky Way Galaxy. This makes Cas A a valuable object to observe in expanding on the field of compact objects.

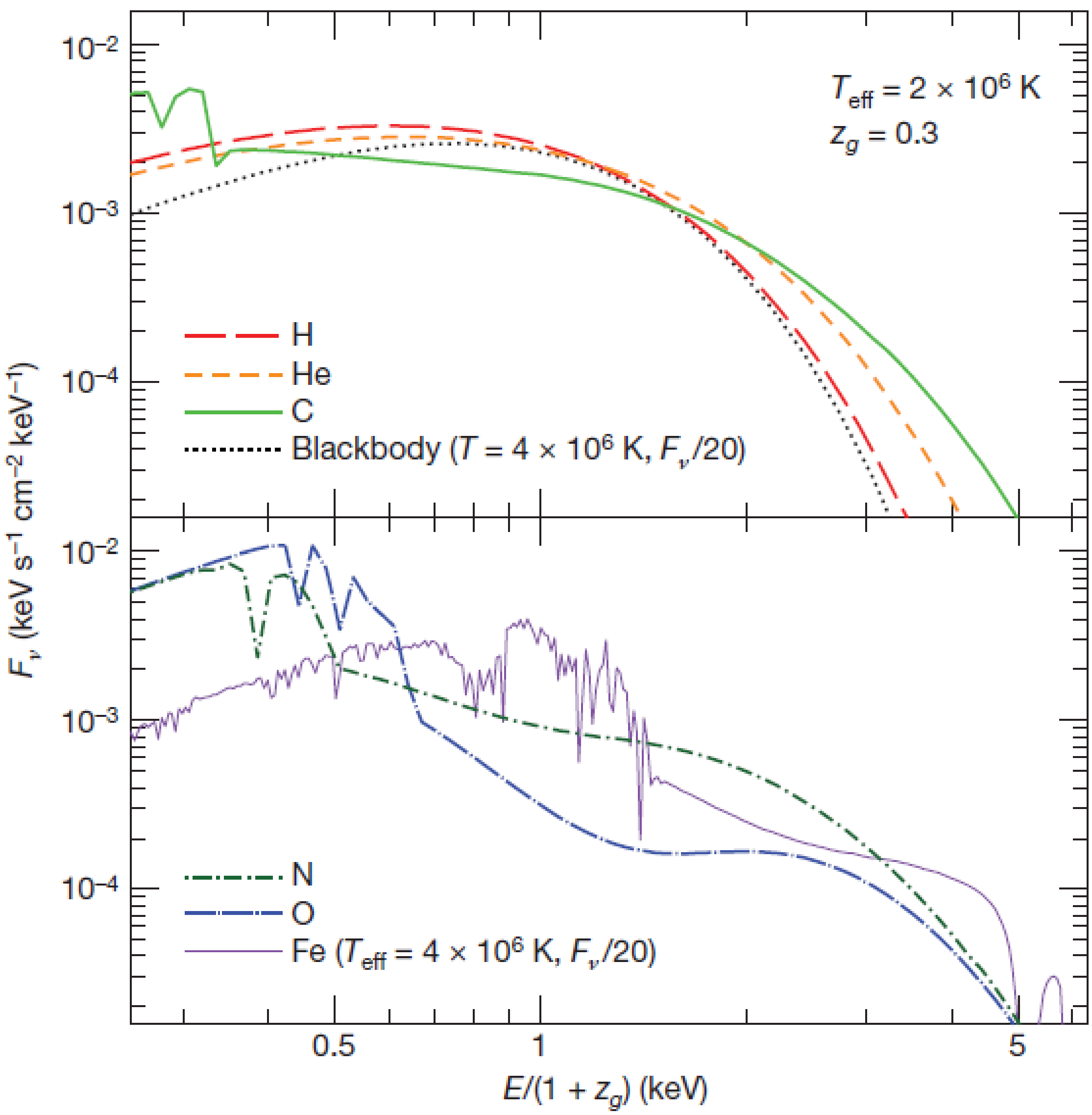
For many years the identity of Cas A eluded scientists. Since Cas A was the product of a supernova, the outcome was one of two possibilities, a neutron star or a black hole. From the observations that we have gathered from Chandra, we know that Cas A is a neutron star. However Cas A is not a typical neutron star in the sense that it does not behave like a pulsar. Using a standard blackbody model on Cas A produces data that is obviously incorrect. Under this model Cas A is estimated to be about 8km in diameter, which is smaller than the minimum size of a neutron star. Using typical methods of retrieving data on Cas A produces results that do not fit our basic models of a neutron star.

Cas A is a radio silent neutron star because hardly any radio waves have been detected. This is uncommon for a young neutron star that should be emitting radio waves as a pulsar. However Cas A does emit x-rays, which could put it in the category of an x-ray pulsar. This brings up the second peculiarity of Cas A; it does not pulsate like a traditional pulsar. There are no observed beams being radiated off into space (Deepto Chakrabarty 2001). The argument can be made that perhaps Cas A's beams are not in the same plane as earth and thus we cannot observe them. With a typical pulsar, the magnetic poles are where the majority of the emission is produced. However, no evidence of hot caps exist on Cas A, which would be an indicator that the star could be a pulsar with emission beams out of view with the Earth. We would identify the hot caps by observing small periodic variation in brightness in these regions.

Perhaps the reason Cas A does not behave like a traditional pulsar is that it has a weak magnetic field. There has been no an observable radio pulsation or pulsar wind. Pulsar winds streams into an ambient medium and creates a standing shockwave, where it becomes decelerated to sub-relativistic speed. Beyond this radius, synchrotron emission increases in the magnetized flow. The fact that Cas A lacks these two occurrences indicates that it has a weak magnetic field. This fact is truly baffling to scientists since all stars have magnetic fields, and thus neutrons stars have strong magnetic fields due to their progenitor stars. So theoretically, Cas A should have a strong magnetic field.

Neutron stars will commonly obtain a thin atmosphere of an abundant element that lingers in the nebula after the supernova. The atmospheric model requires, first and foremost, an understanding on the physical processes happening in relatively compact (up to 10 - 100 grams per c.c.) plasma in Teragauss (100 Megagauss) magnetic fields (Atmospheres of Isolated Neutron Stars n.d.). In these large magnetic fields, even hydrogen is not completely ionized at the desired temperature, and a small percentage of the non-ionized atoms provide the main contribution to the opacity. Using the opacities of strongly magnetized plasmas, scientists can construct models of the neutron stars' atmospheres, which are considerably more complex than the atmospheres of average stars. This is largely because the neutron stars' atmospheres are strongly anisotropic, which is the characteristic of being directionally dependent and moderately dense. The results of the neutron stars' atmospheres display that the magnetic fields considerably affect the spectra, angular distribution and polarization of the emitted thermal-like radiation. Particularly, the spectra deviate considerably from spectra emitted by nonmagnetic atmospheres and the blackbody spectrum (Atmospheres of Isolated Neutron Stars n.d.).

It has been discovered that Cas A has a atmosphere of carbon. After trying to calculate the effects of different elements as atmospheres, along with blackbody radiation, scientists noticed that with a carbon atmosphere, Cas A fit the model for a neutron star (Heinke 2009). Using solely a blackbody diagram to measure the radiation given off by Cas A was giving incorrect data, such as incorrect diameter and showing hot spots on the star where there were no emission (Deepto Chakrabarty 2001). Using the knowledge that neutron stars can have a thin atmosphere of a certain element, scientists started testing elements to see if it produced more accurate results for Cas A.



This is a graph of the data gathered by scientists using the model of a blackbody curve and applying different elements to the curve to produce a better fit of Cas A. The two graph shows the curves produced by a blackbody curve accounting for different elements as atmosphere of the star. The green curve represents carbon, which has been determined as the most accurate result of Cas A (Heinke 2009).

When scientists tested with the element carbon, a more accurate picture of Cas A began to form. Using a blackbody model with a carbon atmosphere, Cas A is determined to be an average sized neutron star, with a diameter of 12-15 km and a mass of around 1.4 solar masses (Heinke 2009). Accounting for the carbon atmosphere also shows that Cas A emits radiation over the entire surface of the star instead of at the poles like a classic pulsar. Cas A is classified as an isolated young cooling neutron star (Heinke 2009). Scientists are finally able to understand the nature of Cas A better, although it still does not behave like an average neutron star. Since Cas A is the youngest observed neutron star in the Milky Way Galaxy, there is much to learn on the early stages of neutron stars from Cas A (Deepto Chakrabarty 2001). Although Cas A demonstrates many abnormalities from average neutron stars, it could just be an anomaly in it behavior, but either way it is valuable to scientists in furthering the field of neutron stars.

In the field of science, progress is made in small steps. Each new discovery adds on a little bit more to scientists' understanding of the field. The history of astrophysics is no different in this sense. As time progresses and more advanced technology is developed, the understandings of neutron stars and other compact objects have become clearer. Through years of research on objects such as Cas A, scientists can build models of neutron stars that are not only theoretical but observable. When scientists first started researching Cas A, hardly any information could be obtained from it. Now decades later, not only is the identity of Cas A known, but there are specific details that have been established. This development is directly related to the advances in technology, such as the x-ray telescope Chandra. As more information is gathered, the more precisely scientists can make conclusions, such as: Cas A does not emit radiation at the poles, so it is not classified as a pulsar; the assumption that the star contains a weak magnetic field can now be concluded; and Cas A shows no signs of an accretion disk, so it can be assumed that it is not part of a binary system nor a black hole. Using the method of elimination, scientists can form a better picture of what possibilities Cas A is and also know what it is not. Today the picture of Cas A is still not completely transparent. Although scientists now know the properties of Cas A, they are still puzzled on the reason behind the neutron star's abnormalities. One can hope that with time and progression in technology, the secrets of Cas A can be discovered and help further the knowledge on neutron stars.

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